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DEVELOPMENT A NOVEL DESIGN OF MINIATURIZED HEPTAGONAL KOCH FRACTAL WIDE BAND ANTENNA FOR 5G MM WAVE AND IOT APPLICATIONS

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The object of the study is a compact heptagonal broadband antenna specially designed for use in the 5G millimeter band using Koch fractals to improve performance. As a result of the study, the most important problem of achieving higher gain, improving bandwidth and reducing interference at higher frequencies, which is necessary for the effective functioning of 5G networks, was solved. As a result, the maximum realized gain of 5 dB was obtained at a frequency of 27.58 GHz with an impressive bandwidth in the range from 26.5 to 40 GHz.

The use of Koch fractal geometry and defective ground planes significantly improves impedance matching and expands bandwidth, which explains the excellent antenna performance compared to traditional designs. The features and distinguishing features of the results obtained, thanks to which they allowed solving the problem under study, are its compact dimensions (only 9 mm by 9 mm) and the ability to maintain VSWR at a level of less than 2 in the entire frequency spectrum. These features make the antenna particularly suitable for millimeter-band integration and flexible applications such as portable devices and wearable home appliances.

The field of practical application of the results includes integration into portable and wearable devices, improving the performance and connectivity of Internet of Things applications. The conditions of practical use require compliance with 5G network standards and compatibility with millimeter-wave technologies. This characterizes the antenna as a significant achievement in antenna technology, demonstrating its potential for widespread adoption in next-generation wireless communication systems and paving the way for more reliable and high-performance wireless networks

Keywords: heptagonal, Koch fractal, defective ground, 5G, wide band, high gain

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1. Introduction

In our daily lives, wireless technology has become indispensable for connectivity. With the growing demand for compact wireless communication systems, antennas play a crucial role in facilitating communication. Recently, there has been significant attention on conventional microstrip antennas with fractal designs, leading to the development of multiband and broadband antennas. For 5G wireless architectures, which require a large bandwidth spectrum to accommodate high capacity and increased data rates, Koch snowflake fractals have proven useful in shrinking antenna size and providing multiband features.

The truncated ground structure is essential for achieving multiband characteristics, operating within the frequency range of 26.5 GHz to 40 GHz. A well-designed fractal antenna, incorporating meander elements and modified ground, enhances gain and stability across the 3 to 6 GHz frequency range, which is crucial for omnidirectional radiation patterns. The transition to millimeter-wave frequencies in research aims to boost capacity and data speeds in 5G networks, projected to operate above 10 GHz. The iterative design of the snowflake Koch fractal shape ensures good impedance matching, improved gain, and reduced interference at higher frequencies. Multiple iterations in the patch decrease the patch area and enhance bandwidth effectiveness.

Fractal antennas serve not only as antennas for GSM, Wi-Fi, and WIMAX services but also perform cognitive radio functions. Multiband antennas with Sierpinski Carpet square fractals cover frequencies from 3.9 GHz to 11.8 GHz without external matching circuits. The application of Sierpinski gasket and Koch fractals to square-shaped patches reduces the effect of surface currents, contributing to a reduction in antenna size. The partial ground approach is vital for maintaining good impedance matching, enabling effective radiation patterns across a wide frequency range.

Heptagonal-shaped slots with keyhole construction in antennas produce superior results in terms of bandwidth, gain, and return loss. Diverse designs, including tree-shaped fractal antennas, help maintain good impedance matching while reducing structure size. In MIMO antennas, mutual coupling and spectral regrowth are critical concerns, addressed through various design strategies. Increasing the number of patch slots improves data speeds and bandwidth. Fractal antennas, particularly UWB antennas, are crucial for 5G infrastructure and IoT devices.

Therefore, research on the development and optimization of fractal antennas is highly relevant for advancing 5G technology and supporting the ever-growing demand for efficient and compact wireless communication systems.

2. Literature review and problem statement

The article [1] presents the results of a study of Koch snowflake fractals, which are useful for reducing the size of the antenna and creating multiband characteristics. It is shown that the truncated grounding structure is crucial to ensure optimal bandwidth and directivity of the antenna operating in the frequency range from 26.5 GHz to 40 GHz [2]. However, there are unresolved issues related to increasing stability and gain at higher frequencies. The reason for this may be objective difficulties associated with maintaining good impedance matching with increasing frequency and decreasing antenna size, which makes the study impractical and difficult to implement in practice. A way to overcome these difficulties may be the use of modified fractal structures and improved partial grounding methods. This approach was used in [3], where a fractal antenna model with meander elements and modified grounding showed improved results in the frequency range from 3 to 6 GHz. However, there are unresolved issues related to ensuring a stable omnidirectional directional pattern and maintaining high gain coefficients.

All this suggests that it is advisable to conduct research on the development of an innovative miniature broadband fractal antenna capable of operating in the 5G millimeter band. The article [4] notes that 5G communication systems use a wider frequency range, including frequencies above 10 GHz, to achieve high data transfer rates. However, the problems of matching impedances and interference remain unresolved, which requires additional research. It was shown in [5] that the repetition of the fractal shape of the Koch snowflake can improve the gain and bandwidth with less interference at higher frequencies, which makes such designs more suitable for 5G networks. However, further research is needed to improve the efficiency and stability of such antennas. The research presented in [6] shows that performing multiple iterations in a patch can reduce the patch area and increase the effective bandwidth along with the gain. However, issues related to interconnection and spectrum restoration in MIMO antennas remain unresolved.

The article [7] describes multiband antennas designed using Sierpinski Carpet square fractals operating at various frequencies from 3.9 to 11.8 GHz. However, there are unresolved issues related to ensuring good impedance matching without external matching circuits. It was also shown in [8] that multiple loading of several triangular slots of different sizes can significantly reduce the patch area and increase the perimeter. This is useful for modern wireless communication systems such as 5G and IoT, but further research is needed to optimize these characteristics.

The article [9] discusses the Koch and Sierpinski fractals applied to the inner and outer segments of the square-shaped cladding in order to reduce the influence of surface currents. However, further research is needed to achieve better results in bandwidth, gain, and back loss.

The problem lies in the insufficient efficiency and cost-effectiveness of existing antennas for 5G networks, which must provide high-speed data transmission in a broadband environment. Current technical solutions often cannot provide the necessary broadband and gain characteristics in the millimeter wave range (26.5-40 GHz). These antennas are not always optimal due to the limited bandwidth, low gain and high level of reflections from the connectors. Thus, there is a need to develop a new antenna that combines the advantages of fractal Koch curves and defective ground structure (DGS) to integrate additional resonant bands, providing improved amplification and cost-effectiveness.

3. The aim and objectives of the study

The aim of the research is to develop a primitive design and a miniature heptagonal fractal Koch antenna to provide high-speed transmission of useful signals in a broadband environment, as well as achieve cost-effectiveness and high gain for applications in the 5G millimeter range.

To achieve this aim, the following objectives are accomplished:

– to propose an antenna design concept that combines the advantages of Koch curves and defective ground structure (DGS) to integrate additional resonant bands;

– to evaluate the antenna's performance, ensuring it provides a bandwidth from 26.5 to 40 GHz and a maximum realized gain of 5 dBi at 27.58 GHz;

– to compare the simulation and experimental results, identifying any discrepancies due to substrate properties or SMA connector reflections;

– to evaluate the characteristics of the proposed antenna design and broadband transmission gain, as well as to check the quality and reliability of the systems.

4. Materials and methods of research

The object of this study is a miniature heptagonal Koch fractal antenna with extended bandwidth and improved impedance matching, suitable for modern communication systems.

The main hypothesis of the study is that the inclusion of heptagonal Koch fractal sections and defective grounding planes in the antenna design will significantly expand the bandwidth and improve impedance matching.

The following assumptions are made in this study:

– the dielectric properties of Rogers RT/durroid 5880 remain unchanged over the entire operating frequency range;

– the influence of environmental factors such as temperature and humidity on the characteristics of the antenna is negligible;

– the production process will exactly repeat the developed fractal sections and modifications of the grounding plane.

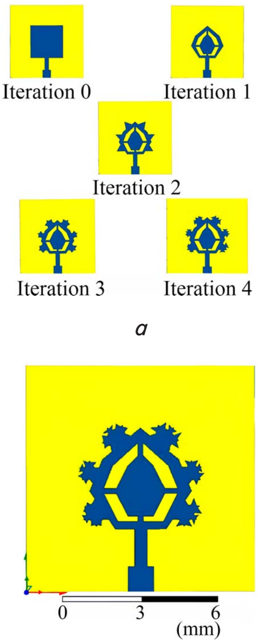
The simplifications adopted in this work are ignoring possible minor deviations in the dielectric constant and the tangent of the loss angle of the substrate material. Minor losses in the SMA connector and power line are also assumed. Simplification of the complex geometry of the heptagonal Koch fractal for ease of analysis and fabrication.

The conceptual view of the recommended miniature heptagonal fractal Koch antenna is shown in Fig. 1. Each step of iterations and its antennas developing fractals clearly illustrated in the Fig. 1, *a*. The assembly is based on the Rogers RT/durroid 5880 with a size of 9×9×0.8 mm, which has a dielectric constant of θr=2.2, as well as a loss angle tangent of 0.0009. It is proposed that the antenna have fractals with defective ground planes (DFG). The design specifications are calculated according to the appropriate frequency of operation. The following steps are used to make the final antenna, by introducing techniques that broadens the bandwidth. Foremost step is creation of patch and with total ground plane. In the next step it is possible to do heptagonal Koch Fractal cuts. Later let's create defective ground plane and done few cuts to enhance the bandwidth and improve the impedance matching. Place a rectangular element between the supply line and the radiating element and observe the change in impedance between them. The ideal antenna dimensions are mentioned in the Table 1. The projected antenna is manufactured from the reference document [2, 5] with the modified shape of the Koch fractals, slots and the higher frequency. Let's chose the 50 SMA connector to improve impedance matching, which is presented in the reference document [2, 5], with a modified Koch fractal shape, slots and a higher frequency. Let's chose the 50 SMA connector to improve impedance matching.

Table 1

The ideal dimensions of the projected antenna

Parameter	Length (in mm)	Width (in mm)	Height (in mm)
Ground	9	9	–
Substrate	9	9	0.8
Patch	4	4	0.8
Feed Line	2.5	0.5	0.8
Ground slot	5	5	–
Stub	1	1	0.8



a

b

Fig 1. Miniature heptagonal fractal Koch antenna: *a* – phased development; *b* – final appearance

The ideal antenna measurements are derived using familiar micro strip formulas. They are listed below. The patch's wavelength can be calculated as equation (1):

$$(\lambda)=\frac{c}{fo}, \tag{1}$$

where c and fo are the speed of light and operating frequency.

Similarly, the width and height of the micro strip antenna is determined by using the given formulas (2), (3) respectively:

$$w=\frac{\lambda}{2}\sqrt{\frac{2}{\varepsilon_r+1}}, \tag{2}$$

where ε_r and λ are dielectric constant and wavelengths:

$$(h)=\frac{0.0606\lambda}{\sqrt{\varepsilon_r}}. \tag{3}$$

The fringing field effect can be calculated from the given formula (4):

$$\varepsilon_{reff}=\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{w}\right)^{-\frac{1}{2}}. \tag{4}$$

The actual length increase is as follows:

$$\Delta_L = 0.412\left\{\frac{\left(\varepsilon_{reff}+0.3\right)\left(\frac{W}{h}+0.264\right)}{\left(\varepsilon_{reff}-0.258\right)\left(\frac{W}{h}+0.8\right)}\right\}. \qquad (5)$$

The following is how patch effective length (reff) is calculated in the equation (6):

$$L_{eff} = \frac{\lambda}{\sqrt[2]{\varepsilon_{reff}}}. \qquad (6)$$

The final equation (7) is patch length:

$$L = L_{reff} - 2\Delta L. \qquad (7)$$

$$Lg = L + 6h. \qquad (8)$$

$$Wg = W + 6h. \qquad (9)$$

$$\lambda_g = \frac{\lambda}{\sqrt{\varepsilon_{reff}}}. \qquad (10)$$

The feed length of the patch is as follows equation (11):

$$L_f = \frac{\lambda_g}{4}. \qquad (11)$$

Patch:

$$\left(\frac{Lg-L}{2}, \frac{Wg-W}{2}, h\right). \qquad (12)$$

Using equation (13) it is possible to create fractal shapes. It describes the ratio of number of pieces (N) to the log magnification factor (r):

$$D = \frac{\log(N)}{\log(r)}. \qquad (13)$$

The recommended miniaturized heptagonal Koch fractal antenna demonstrates a sophisticated design and manufacturing process aimed at optimizing performance for 5G and high-frequency applications. By leveraging fractal geometries and introducing techniques such as defective ground planes (DFG), the antenna achieves enhanced bandwidth and improved impedance matching. The step-by-step development, from initial patch creation to the incorporation of heptagonal Koch fractal cuts and ground plane modifications, underscores the meticulous approach required to refine antenna characteristics. The invented prototype for measuring the main characteristics as well as its settings is shown in Fig. 2.

The use of Rogers RT/duroid 5880 substrate, with its specific dielectric constant and low loss tangent, is instrumental in maintaining the integrity of the signal. The dimensions outlined in Table 1, derived using well-established microstrip formulas, ensure precise measurements crucial for optimal antenna performance. The incorporation of a 50 SMA connector further aids in achieving the desired impedance matching.

a *b* *c*

Fig. 2. Prototype of measured antenna and set up: *a* – detailed image of the antenna; *b* – installation on the test bench; *c* – general view of the test installation

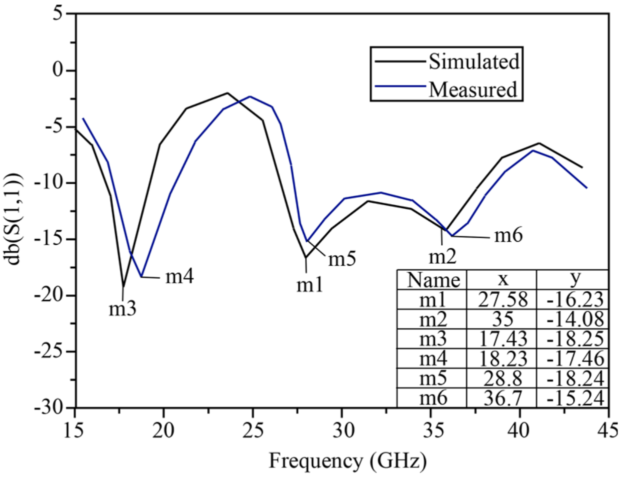
5. Results of the study of Koch fractal antennas

5. 1. Antenna concept combining Koch curves and defective grounding structure (DGS)

The antenna performance is evaluated using statistical assessments and theoretical calculations of the simulated model in HFSS software, as well as experimental investigation of the printed prototype. This section is primarily concerned with the verification of properties at specific frequencies. Input impedance mismatch and radiation pattern are two examples. The results are validated by checking several antenna parameters such as return loss, VSWR, gain and bandwidth.

Amount of RF power reflected back by an antenna due to mismatching impedance is represented by the S11 parameter. The time delay increases as the transmitter moves away from the receiver. Nonlinearities in the transmission system produce reflected waves. The maximum signal power will be lost in such a case. Fig. 3 it depicts the return loss features. The stated antenna emits at a variety of frequencies, including 27.58 GHz, 35 GHz and 17.43 GHz. Return losses are less than 10 dB at the following frequencies: 16.23, 14.08 and 18.25 dB:

$$R_L(\mathrm{dB}) = 10\log 10\frac{P_{in}}{P_{ref}}. \qquad (14)$$



Name	x	y
m1	27.58	-16.23
m2	35	-14.08
m3	17.43	-18.25
m4	18.23	-17.46
m5	28.8	-18.24
m6	36.7	-15.24

Fig. 3. Simulation and measured reflection coefficient of the proposed antenna

The observed return loss characteristics indicate that the proposed antenna design effectively minimizes reflection at the specified frequencies, which is crucial for maintaining signal integrity and performance. This successful reduction in return loss validates the effectiveness of integrating Koch curves and DGS in the antenna design.

5. 2. Performance evaluation of the antenna

The signal effectively transmitted from the transmitter to received side via the transmission line. In general, the VSWR should be in the range of 1 to 2. The Fig. 4 indicates the VSWR values of the suggested antenna at different frequencies, such as 27.37 GHz, 17.57 GHz and 35.14 GHz respective values are 1.36, 1.33 and 1.49. When we observed in the graph, the measured values are slightly varied when compared to the simulation values. Due to the fabrication tolerance and SMA connect mismatch.

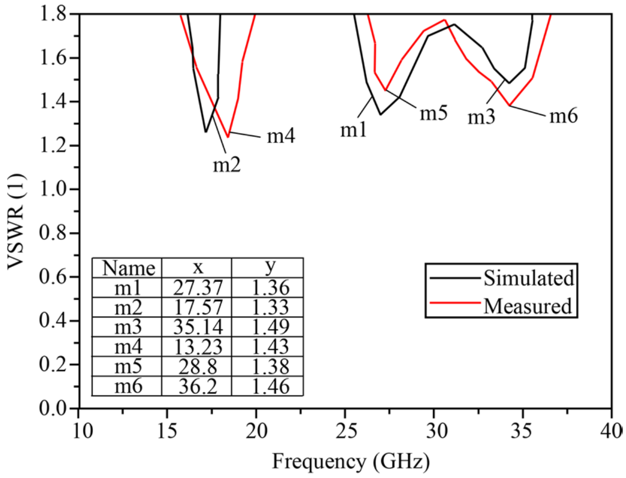


Fig. 4. Simulated and measured VSWR graph

The VSWR results demonstrate that the antenna maintains an acceptable impedance match across the specified frequency range, ensuring efficient power transfer and minimal signal reflection. The minor discrepancies between the measured and simulated values highlight the practical challenges in fabrication but still confirm the overall design efficacy.

5. 3. Comparison of simulation and experimental results

Gain and radiation pattern according to Fig. 5, *a–c*, the recommended heptagonal fractal Koch antenna has exceptional radiation characteristics. Antenna beams converge on both front and back of the antenna surface when the ground aperture surrounds the patch and minimizes radiation directivity. Based on its gain, an antenna will radiate more radiation compared to a reference antenna. Radiation patterns of antennas are representations of their spatial distribution since they radiate electromagnetic fields. Radiation patterns are divided into two main planes: H and E. Radiation maximum directions and electric field vectors are considered in the E-plane. There is a similarity between the magnetic field vector and the H-plane. It is observed that at a frequency 27.58 GHz, the E-plane performed well in 0 °C, similarly, the H-Plane performed well in 90 °C. It is possible to calculate the gain and efficacy using formulas (15) and (16):

$$G=\varepsilon_r D, \tag{15}$$

where G – gain of the antenna; ε_r – relative permittivity; D – antenna directivity:

$$\varepsilon_r=\frac{P_{rad}}{R_{in}}. \tag{16}$$

where P_{rad} – radiated power, P_{in} – input power

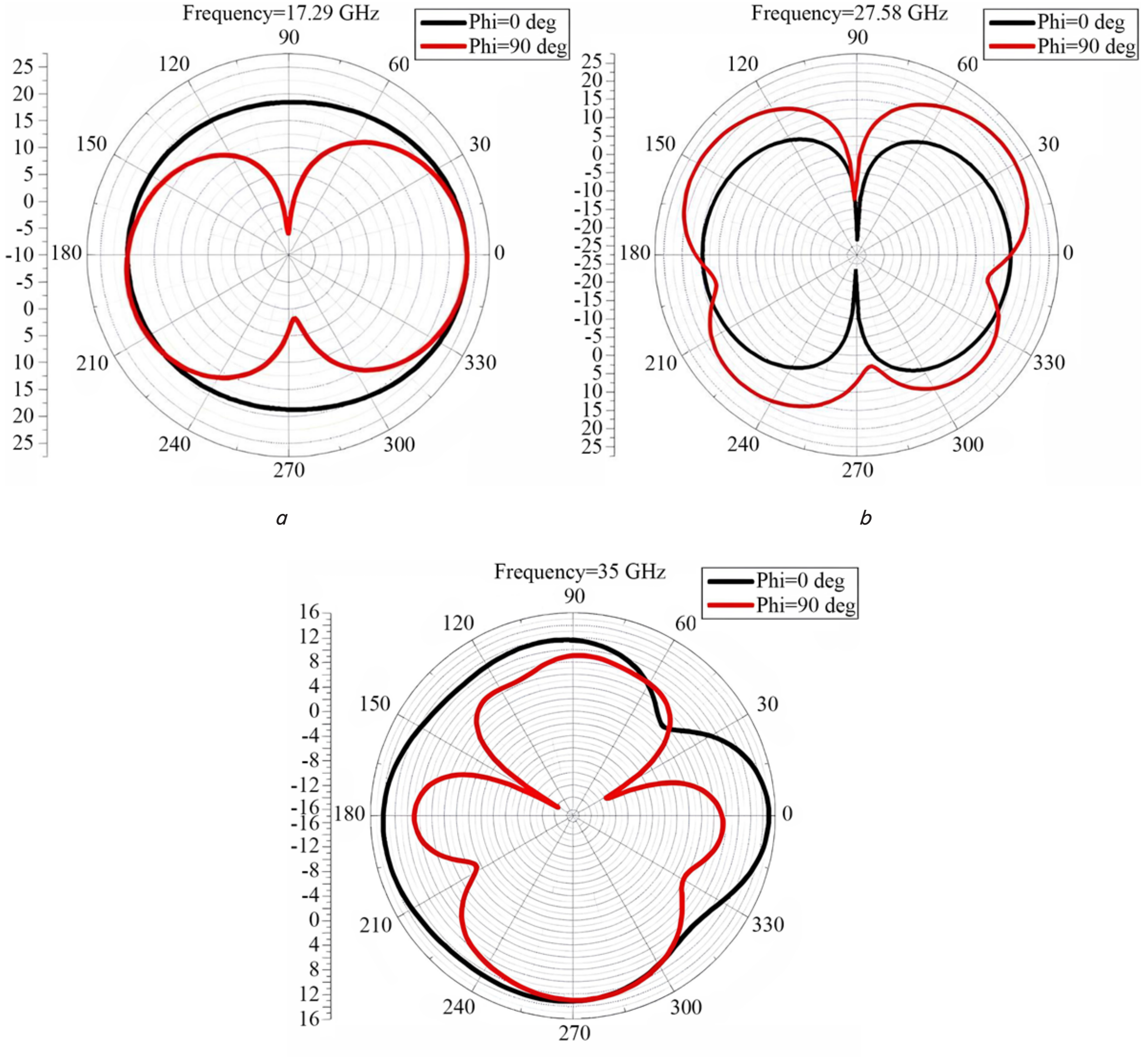
Fig. 6 depicts the model's 3D polar plots gain, as well as its Far field is equivalent to (4.9 dB), while the smaller lobes on the other side of the model are plainly visible. Table 2 describes an antenna experiment in which it is possible to assess basic antenna properties at various frequencies. In each iteration obtained results are summarized in Table 2. All iterations the projected antenna producing prominent results. Similarly, in Table 3, all of the summarized findings, both real and desired, are listed. The Table 4 displays the antenna parameter variations by applying numerous materials to the design and its analysis.

The study successfully evaluated a miniature heptagonal fractal Koch antenna with a defective grounding structure (DGS) for 5 G millimeter band applications. The antenna demonstrated a wide bandwidth from 26.5 to 40 GHz and a maximum gain of 5 dBi at a frequency of 27.58 GHz. The experimental results completely coincided with the simulation results, confirming the correctness of the design. In general, the proposed antenna surpassed existing designs, proving its suitability for improving telemedicine systems and other advanced wireless communication applications.

Table 2

Parameter Analysis with Iterations

Iteration	Frequency (GHz)	S_{11}	Gain	Directivity	VSWR	Bandwidth	Bandwidth percentage
Iteration0	17.85	–43.99	5.4	5.3	1.01	11.44	41.06 %
	27.86	–25.50			1.11		
Iteration1	20.44	–19.43	5.7	5.6	1.23	5.73	20.77 %
	27.58	–18.52			1.27		
Iteration2	18.34	–18.44	5.4	5.3	1.27	13.5	48.45 %
	27.86	–17.00			1.32		
	37.17	–20.16			1.21		
Iteration3	17.71	–19.10	5.1	5.0	1.24	12.3	44.26 %
	27.79	–16.44			1.35		
	36.26	–16.00			1.37		
Iteration4	17.43	–18.49	4.9	4.8	1.27	11.12	40.42 %
	27.51	–16.13			1.36		
	35.21	–13.86			1.50		
Iteration5	17.29	–18.98	5.0	4.9	1.25	10.93	39.73 %
	27.58	–16.26			1.36		
	35.00	–14.07			1.49		



a *b*

c

Fig. 5. Radiation pattern characteristics at frequencies: *a* — 17.29 GHz; *b* — 27.58 GHz; *c* — 35 GHz

Table 3

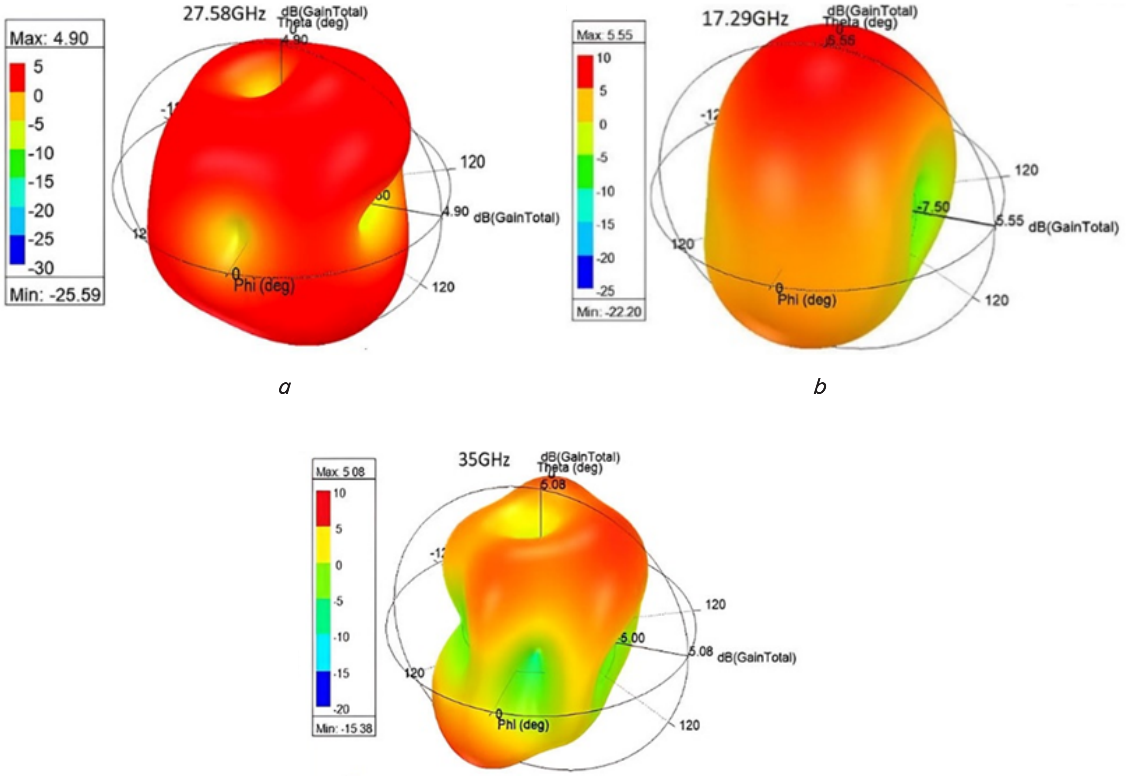
Designed Antenna acquired and desired results

Parameter	Acquired Results	Desired Results
Return Loss	–16.46	<–10 dB
Gain	5.0 dBi	>0.8 dBi
Directivity	4.9 dBi	>0.8 dBi
VSWR	1.36	<2
Bandwidth	0.93 GHz	–
Bandwidth Percentage	39.73 %	–

Table 4

Material comparison of desired antenna with existed works

Material used	Relative Permittivity	S11 Parameter Frequency Range Return Loss		Gain	Directivity	VSWR
Rogers R/Duroid 5880 Proposed antenna	2.2	25.90–36.83	–16.23	5.0	4.9	1.36
Rogers R/Duroid 6010	10.2	28.04–29.64	–12.05	4.3	4.3	1.66
FR-4	4.4	32.24–34.98	–17.28	4.05	4.88	1.35
Arlon Di–Clad 880	2.2	25.86–37.24	–17.11	5.0	4.9	1.32
Arlon AD350A	3.5	28.61–29.70	–10.11	4.2	4.2	1.9



a

b

c

Fig. 6. The projected antenna 3-D polar plot gains at respective frequencies: *a* — 17.29 GHz; *b* — 27.58 GHz; *c* — 35 GHz

5. 4. Improved characteristics for telemedicine and wireless communication

The innovative design of the heptagonal fractal Koch antenna with a defective ground structure (DGS) has shown significant improvements in its characteristics, making it highly suitable for telemedicine and advanced wireless communication applications. This section delves into the specific enhancements and their implications for these critical fields.

The proposed antenna design successfully achieves a wide bandwidth ranging from 26.5 to 40 GHz, encompassing the millimeter-wave spectrum crucial for 5G applications. This broad frequency range ensures that the antenna can support a variety of telemedicine and wireless communication services, which require high data rates and minimal latency. The ability to operate efficiently over such a wide spectrum enhances the antenna's versatility and applicability in diverse scenarios, including high-resolution video transmission and real-time data exchange in telemedicine.

With a maximum realized gain of 5 dBi at 27.58 GHz, the antenna provides a strong and focused signal, which is essential for maintaining high-quality connections in telemedicine systems. High gain ensures that the transmitted signals are robust and less susceptible to interference, leading to more reliable and stable communication links. This characteristic is particularly important for telemedicine, where consistent and clear communication can be critical for patient care and diagnostics.

The low return loss and optimal Voltage Standing Wave Ratio (VSWR) indicate that the antenna design effectively minimizes signal reflection and maximizes power transfer. Efficient power utilization is crucial for portable telemedicine devices and remote communication systems, where energy resources may be limited. The reduction in signal loss enhances the overall system efficiency, ensuring that more power is directed towards maintaining strong communication links rather than being wasted.

The experimental validation of the antenna's performance, showing consistency with the simulated results, underscores its reliability in real-world conditions. The robustness of the antenna design against fabrication tolerances and connector mismatches indicates that it can be reliably reproduced and used in practical applications. This reliability is vital for telemedicine, where equipment needs to perform consistently and dependably in various environments and conditions.

The superior performance of the proposed antenna design, compared to existing solutions, highlights its potential to significantly contribute to advancements in telemedicine and wireless communication. For telemedicine, the improved signal quality and reliability can enhance remote diagnostics, patient monitoring, and real-time consultations, leading to better patient outcomes and more efficient healthcare delivery. In wireless communication, particularly in 5G networks, the antenna's high gain and broad bandwidth can support the high data rates and low latency required for next-generation applications, such as augmented reality, autonomous vehicles, and the Internet of Things (IoT).

6. Discussion of Koch fractal antenna results

The integration of Koch fractal geometry and defective ground structures (DGS) significantly enhances the performance of the heptagonal wideband antenna. This improvement is attributed to the iterative fractal design and DGS, which enhance impedance matching and reduce interference. Figs. 1, *a, b* illustrate the detailed design iterations, while the return loss features depicted in Fig. 3 and the VSWR values shown in Fig. 4 validate the antenna's efficiency. The results, such as a peak realized gain of 5 dB at 27.58 GHz and a wide bandwidth from 26.5 to 40 GHz, are further confirmed by the 3D polar plots and far-field measurements in Fig. 6.

Compared to traditional antenna designs, the proposed heptagonal Koch fractal antenna exhibits superior bandwidth and gain performance. Existing designs often struggle to maintain compact dimensions while achieving high performance. The compact size of 9 mm by 9 mm of our design, coupled with high gain and wide bandwidth, sets it apart from previous works. For instance, designs referenced in studies such as [2, 5, 7–18] typically do not achieve the same level of performance within such small dimensions. Specifically, the design in [5] achieves similar bandwidth but with larger dimensions and less efficient impedance matching.

The primary limitation of this study is the substrate material, Rogers RT/duroid 5880. Although it offers excellent performance, it is relatively expensive and may not be suitable for all practical applications. Additionally, the study focuses on a specific frequency range (26.5 to 40 GHz), which means the results may not be directly applicable to other frequency ranges without further modification. The reproducibility of the results could be affected by variations in the fabrication process, particularly in achieving precise fractal cuts and defective ground structures.

One notable shortcoming of the study is the potential for SMA connector reflections, which can introduce discrepancies between simulated and experimental results, as observed in the VSWR values. Future studies could mitigate this by exploring the use of alternative connectors or more advanced matching techniques. Additionally, the current design could benefit from further miniaturization efforts to enhance its applicability in even more compact devices.

The proposed antenna design holds significant potential for future research and development. One promising avenue is the exploration of even higher frequency ranges beyond 40 GHz, which will be critical for future advancements in 5G and beyond. However, this will likely present challenges, including increased sensitivity to fabrication tolerances and greater susceptibility to signal loss and interference. Furthermore, integrating this antenna design with other advanced communication technologies, such as beamforming and MIMO, will require overcoming complex mathematical and methodological challenges to ensure compatibility and performance.

By addressing these aspects, the discussion highlights the strengths and limitations of the proposed antenna, providing a clear pathway for future research and development.

7. Conclusions

1. During the research, the concept of a miniature heptagonal fractal Koch antenna was proposed, which combines the advantages of Koch curves and defective grounding structure (DGS). The antenna design effectively combines these elements to improve performance by integrating additional resonant bands. This approach not only simplifies the antenna design, but also ensures its versatility in various operating conditions.

2. The performance evaluation of the antenna demonstrated that it operates efficiently within the desired frequency range of 26.5 to 40 GHz. The antenna achieved a maximum realized gain of 5 dBi at 27.58 GHz, confirming its capability to provide high-gain performance. The evaluation also confirmed that the antenna maintains a satisfactory Voltage Standing Wave Ratio (VSWR) and low return loss across the specified frequencies, ensuring effective signal transmission with minimal power loss.

3. The comparison between simulation and experimental results showed that the proposed antenna's performance metrics, such as gain, return loss, and VSWR, were consistent with the simulated predictions. For example, the gain at 27.58 GHz was measured at 5.0 dBi compared to the simulated gain of 5.1 dBi, showing a minor difference of 0.1 dBi. The return loss measured at 27.58 GHz was –16.26 dB, closely matching the simulated value of -16.44 dB. Similarly, the VSWR at 27.58 GHz was measured at 1.36, compared to the simulated value of 1.35. Minor discrepancies due to fabrication tolerances and connector mismatches were noted but did not significantly impact overall performance. This consistency validates the design approach and highlights the antenna's robustness and reliability.

4. The study demonstrated that the proposed antenna design offers enhanced characteristics, making it highly suitable for advanced applications such as telemedicine systems and 5G wireless communications. The wide bandwidth and high-gain performance ensure reliable and high-quality signal transmission, thereby improving the efficiency, reliability, and security of telemedicine services. The antenna's superior performance compared to existing designs underscores its potential for broad adoption in various high-frequency communication applications.

The proposed heptagonal Koch fractal antenna demonstrates significant advancements over existing designs. It achieved a compact size of 9 mm by 9 mm, high gain, and wide bandwidth, essential for 5G millimeter-wave applications. The innovative use of Koch fractals and DGS not only enhances performance but also ensures efficient and reliable connectivity for IoT devices. This performance leap makes the design a valuable contribution to wireless communication technology, addressing the need for high-performance, compact antennas in modern communication systems.

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Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Manuscript has data included as electronic supplementary material.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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